Perturbation Modeling and Data Analysis in ASIAEX

Kevin B. Smith
Code PH/Sk, Department of Physics
Naval Postgraduate School
Monterey, CA 93943
phone: (831) 656-2107 fax: (831) 656-2084 email: kbsmith@nps.navy.mil

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LONG-TERM GOALS

Shallow water acoustics and the performance of sonar systems in littoral environments are critical areas of interest to the US Navy. In response to this, the Office of Naval Research sponsored a series of acoustics experiments in the East and South China Seas, hereafter referred to as ASIAEX. Components of these experiments included studies of shallow water reverberation, geoacoustic properties, and short-range propagation variability. The long-term goals of this study are to provide a better understanding of shallow water reverberation, its statistics, and the primary mechanisms that define its structure, as well as the influence of geoacoustic and water column variability on shallow water propagation. By improving our understanding, the negative influence of such variability on active systems may be reduced through smarter data processing.

OBJECTIVES

The objective of this research was to model various propagation features within the East China Sea component of the ASIAEX experiment. Specifically, the influence of propagation on both interface and volume reverberation over a large bandwidth of frequencies were examined and compared with data collected, direct path propagation through water volume fluctuations was computed and compared with data collected, and the influence of environmental variability on effective bottom attenuation was investigated. By understanding the role of the acoustic propagation in such signals, a more clear description of the underlying role of propagation on scattering mechanisms, direct path variability, and bottom attenuation has emerged. This may provide important information on the statistics of the signal, enhancing the use of active systems by accounting for some of the structure in the signal processing.

APPROACH

In shallow water environments, our understanding of the primary mechanisms driving the character of the reverberation signal is not clear. This is due in part to the complicated propagation (dominated by multipaths) and the unknown influences of sediment and water column volume scattering. One of the elements of this study was to examine some of the influences of the complicated shallow water propagation on the character of the reverberation signal.
Also during the East China Sea portion of the experiment, data collected by a group from APL-UW (led by Peter Dahl) examined the multipath structure observed at a relatively short distance (~ 500m) [1]. Various multipaths were distinguishable and identifiable, including a direct water-bourne path that should be unaffected by the boundaries, and therefore independent of sea state or bottom properties. Any observed variability in this arrival should then be due to volume fluctuations within

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14. ABSTRACT
Shallow water acoustics and the performance of sonar systems in littoral environments are critical areas of interest to the US Navy. In response to this, the Office of Naval Research sponsored a series of acoustics experiments in the East and South China Seas, hereafter referred to as ASIAEX. Components of these experiments included studies of shallow water reverberation, geoacoustic properties, and short-range propagation variability. The long-term goals of this study are to provide a better understanding of shallow water reverberation, its statistics, and the primary mechanisms that define its structure, as well as the influence of geoacoustic and water column variability on shallow water propagation. By improving our understanding, the negative influence of such variability on active systems may be reduced through smarter data processing.

15. SUBJECT TERMS

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the environment, most notably internal wave disturbances. The interaction of such perturbations on the direct path propagation was investigated in this study.

Finally, it is recognized that a good model of local geoacoustic properties is needed to accurately predict seafloor (both interface and volume) reverberation levels. While estimates of sound speed and density have been made consistent with the data available, an estimate for the bottom attenuation is more difficult due to its dependence on acoustic frequency. Furthermore, recent analysis of other shallow water environments has suggested that the standard model of linear frequency dependence on sediment attenuation does not fit available data, but rather a non-linear dependence has been proposed [2]. It is unclear, however, whether such non-linear response is due to the physical loss mechanisms of the sediment volume, or whether it is an indirect effect caused by perturbations to the standard homogeneous half-space model (e.g., rough water/sediment interface, sediment sound speed gradient, rough sub-layer, etc). The influence of such effects on the frequency dependence of the bottom layer was examined in this study.

The underlying acoustic model used in this work is the parabolic equation (PE) model. Specifically, the Monterey-Miami PE (MMPE) Model [3] was employed.

In order to examine the effective frequency dependence of bottom attenuation due to environmental perturbations, a direct set of forward and inversion matching calculations were performed. Over a frequency range of roughly 100 Hz to 1.5 kHz, the model was used to compute the downrange propagation of acoustic energy in the presence of a variety of environmental perturbations, including varying water column sound speed profiles, varying bottom sound speed gradients, rough water/sediment and sediment/basement interfaces of varying rms scales, and varying levels of sediment/basement volume sound speed and density fluctations. In each case, the sediment had the standard attenuation model with linear dependence on frequency.

Subsequent calculations modeled an average, range-independent environment. However, the frequency dependence was then allowed to vary from 0.75 to 2.25. By performing a set of standard matched-field processing techniques, estimates were made of the effective attenuation at each frequency. The results provided the effective frequency dependence of sediment attenuation in the presence of such perturbations. Progress on this work was communicated to Drs. James Miller (URI), David Knobles (ARL-UT) and Zijun Zhou (GTech), co-investigators on the ASIAEX program.

The investigation into the water column variability effects on direct path propagation was a collaborative study with Peter Dahl (APL-UW). Based on the experimental configuration described by him in the Melville's cruise report [1], the 2 msec pulses were modeled. By extracting the first arrival corresponding to the direct, water-bourne path, the data was compared to measurements made aboard the Melville. Consistent with the experimental geometry, the modeled data was also extracted at the specific depths of the array elements. Vertical statistics (coherence) were then be obtained.

Concurrent with the acoustic measurements, the water column was sampled nearby by the Shi-Yan 3. Water column sound speed data provided by Yiquan Qi (SCSIO) indicated the level of variability over time. By using such sound speed data in the model, an estimate of the level of fluctuations in the vertical coherence was obtained. Oceanographic models that produce more continuous perturbations consistent with the area were then used in order to develop more realistic statistics of the vertical coherence structure. Specifically, the turbulent-scale perturbations introduced were based on the models described by Duda and Trivett [4] and Henyey, et al. [5]. The results of this analysis were then compared with similar analysis of the measured data.

In order to predict reverberation levels, a formal treatment of backscatter has been performed in the context of the PE approximation [6]. Essentially, this model incorporates the Born approximation into a two-way PE model, assuming multiple forward scattering occurs due to all environmental fluctuations, but only single backscattering from each scattering patch. Both interface roughness and

volume sound speed inhomogeneities were treated. It furthermore assumed a constant scattering strength could be used to characterize an entire scattering patch, thereby neglecting much of the details of the specific scattering mechanisms and dominating the result by the total field predicted at the scattering patch. Thus, the statistics and general structure of the predicted reverberation return are solely a function of the propagation.

The theory for the predicted reverberation pressure levels was developed in FY00-02, and is described in Smith, et al. [7]. The output of the model is a normalized, time-domain structure of the reverberation signal due to each interface (water/bottom and bottom/subbottom) and the bottom volume. Each run can be performed for any source/receiver geometry along a vertical array and for any combination of environmental perturbations. The effects of variations in the environment then required many multiple runs, one for each realization of the perturbations.

Such results will be compared with measured data to determine the influence of propagation and, hopefully, help discriminate specific scattering mechanisms. Specifically, the vertical coherence of the reverberation signal measured along the vertical array will be examined. Based on previous theoretical work by Ivakin [8], interface and volume reverberation should have distinguishable vertical coherence for large bandwidth (bandwidth to center frequency ratios of order 1 or larger). Furthermore, volume reverberation coherence should be relatively independent of bandwidth, while interface reverberation coherence should show enhanced coherence at large bandwidth, thus making it distinguishable from the volume. At smaller bandwidths, the interface reverberation coherence degrades to similar levels as the volume.

WORK COMPLETED

The theoretical development of the PE reverberation model and the introduction of bottom interface and volume variability was completed in FY00-01. In FY02, the inclusion of sediment density fluctuations was treated, as well as the introduction of measured sound speed profile data, a subbottom interface, and geoacoustic parameters as measured during the East China Sea part of ASIAEX. This completed the development of the reverberation model. In FY03, the main focus was on the analysis of generated data and the initial analysis of the measured SUS reverberation data. Additional environmental perturbations and experimental configurations were also incorporated into the model results. Specifically, the influence of water volume turbulence and multiple radial interface/volume perturbations were examined. A model of the SUS source spectrum was also introduced in the postprocessing.

For the effective attenuation studies, the same types of bottom perturbations were included. However, different types of perturbations combinations were employed. In some cases, only a single sediment half-space was defined (no subbottom interface). Calculations were then made which examined only the influence of changes in sediment sound speed gradient, which varied from 0.5 – 2.0 m/s/m. The next set of data were generated with no sound speed gradient, but the bottom interface rms roughness was varied from 1 – 5 m. Next, the interface was flat, but the bottom volume had rms fluctuations ranging from 5 – 15m/s in sound speed (with corresponding fluctuations in bottom density). The volume fluctuations were then turned off and a subbottom interface was added with rms fluctuations ranging from 1 – 5 m. Finally, an environment was computed with both interfaces of varying roughness and perturbations in the bottom volume. For each of these perturbed environments, the sediment attenuation was held constant. Subsequent to these calculations, a corresponding set of data were computed for the average environment (without perturbations) with varying levels of sediment attenuation. All data was computed over the frequency range from 10 – 500 Hz. By correlating the

results of the perturbed and unperturbed data, the effective sediment attenuation as a function of frequency was estimated.
In order to study the variability of the water-bourne propagation path and compare with data collected by Peter Dahl's group at APL-UW, it was necessary to adapt the MMPE model to compute the same type of source response function as used during the experiment. In addition, a model of the water volume turbulence was incorporated. The data computed was then sampled at approximately the appropriate range and depths of the short aperture arrays employed. The vertical coherence of the signals were then computed along the sub-arrays for a variety of turbulent perturbation scales and background sound speed profiles.

RESULTS

There were several very interesting outcomes of the reverberation analysis from this past year. From the model results, it was confirmed that the interface and volume reverberation returns do show unique vertical coherence structures at large bandwidth, but *only when the Hanning window source spectrum was used*. When the SUS source spectrum consistent with the experimental data was employed however, this distinction broke down. This is presumably due to the structure of the SUS spectrum, which responds like several narrowband sources. Figure 1 displays the difference between the two source spectra over the band investigated, 100 – 600 Hz. Figure 2 shows the effect of bandwidth on the vertical coherence when the Hanning spectrum is used, while Fig. 3 displays the same results with the SUS spectrum. In the former case, the volume reverberation signature is clearly seen to decorrelate more rapidly for larger bandwidths, but the signal become less distinguishable as the bandwidth is reduced. In the latter case, all reverberation signals decorrelate at nearly the same rate, providing no distinguishable features between interface and volume returns. Another unexpected feature of the reverberation coherence was that, for both types of source spectra, the volume reverberation coherence was found to consistently improve slightly with decreasing bandwidth. This is in contrast to the previous theoretical work and the physical mechanism behind this effect is still being considered.
Upon examination of the measured reverberation data, peak vertical correlation curves display a fairly narrow coherence depth. This might be expected to be consistent with volume reverberation, although the previous analysis with the SUS spectrum suggests this may be indeterminate. However, it is interesting to note that the coherence appears to improve slightly with decreasing bandwidth, consistent with the modeling results for the volume. Figure 4 displays these results.

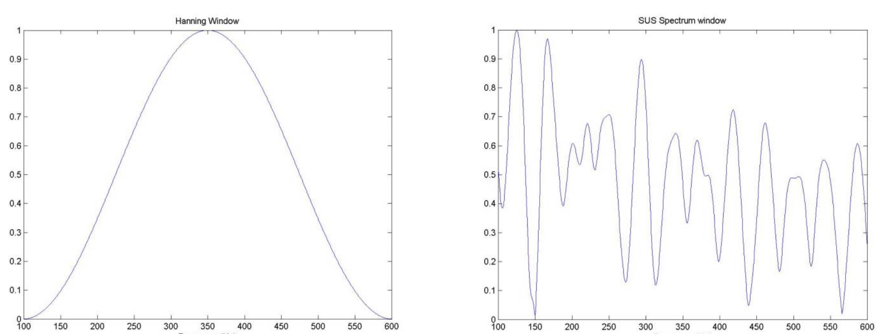

Figure 1: Modeled source spectra: Hanning (left) and 38g SUS detonated at 48 m (right).

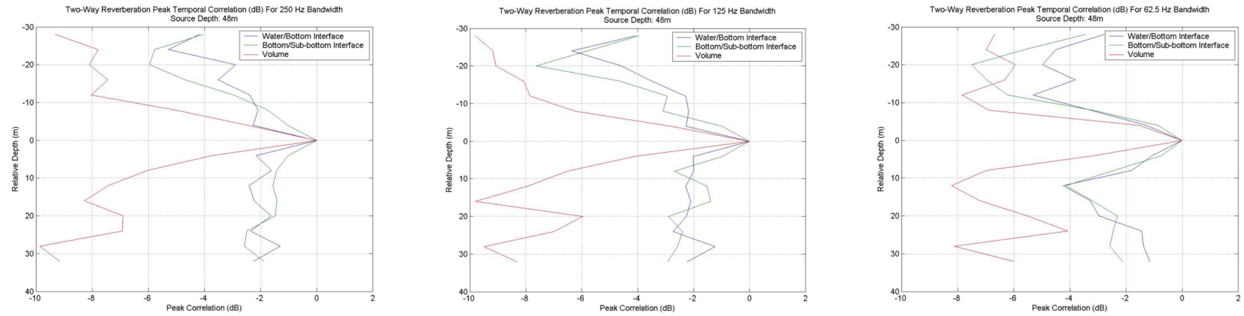

Figure 2: Peak vertical coherence curves of predicted reverberation from water/bottom interface (blue curves), bottom/subbottom interface (green curves), and bottom volume (red curves). A Hanning source spectrum is employed. The bandwidth is reduced from 250 Hz (left plot) to 125 Hz (middle plot) to 62.5 Hz (right plot).

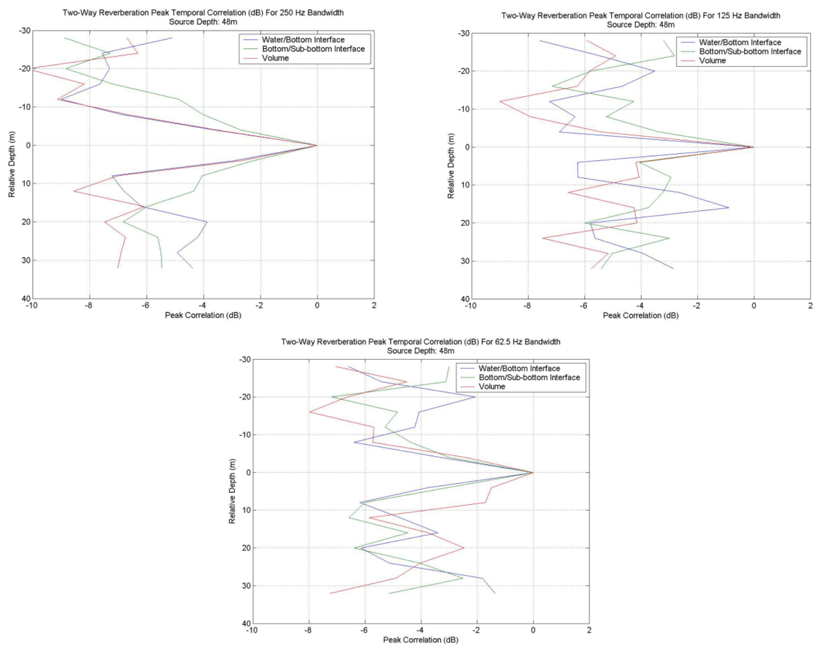

Figure 3: Peak vertical coherence curves of predicted reverberation from water/bottom interface (blue curves), bottom/subbottom interface (green curves), and bottom volume (red curves). A SUS source spectrum consistent with the experimental data is employed. The bandwidth is reduced from 250 Hz (left plot) to 125 Hz (middle plot) to 62.5 Hz (right plot).

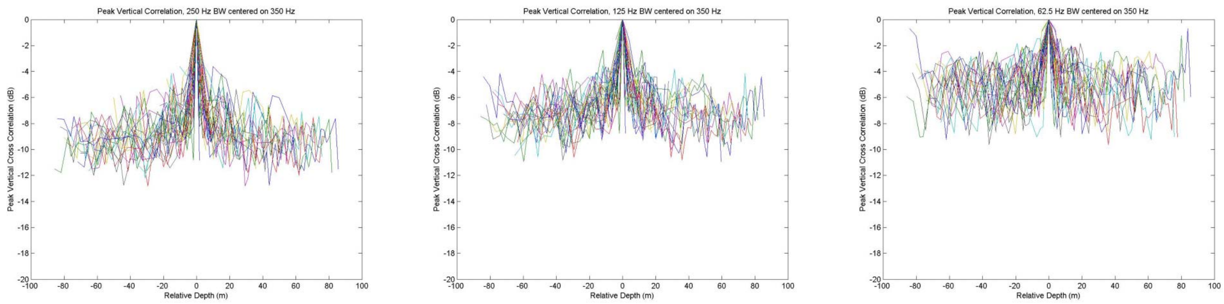

Figure 4: Peak vertical coherence curves of measured reverberation from a single 38g detonation. The bandwidth is reduced from 250 Hz (left plot) to 125 Hz (middle plot) to 62.5 Hz (right plot).

When the influence of environmental fluctuations on the effective frequency dependence of bottom attenuation was examined, it was found that volume and/or subbottom variability introduced the most significant frequency dependence. Specifically, if the bottom volume had a significant sound speed gradient, or if the subbottom interface roughness was significant, lower frequencies penetrating to deeper depths were more likely to be refracted/scattered back into the water column thereby lowering the effective attenuation at those frequencies. This is in contrast to some observations at higher frequencies which suggest coefficients > 1.0, and this analysis is on-going to determine what factors may increase the observed coefficient in shallow water environments. A speculation on the general effects of variability on effective bottom attenuation was presented of the form provided in Fig. 5.

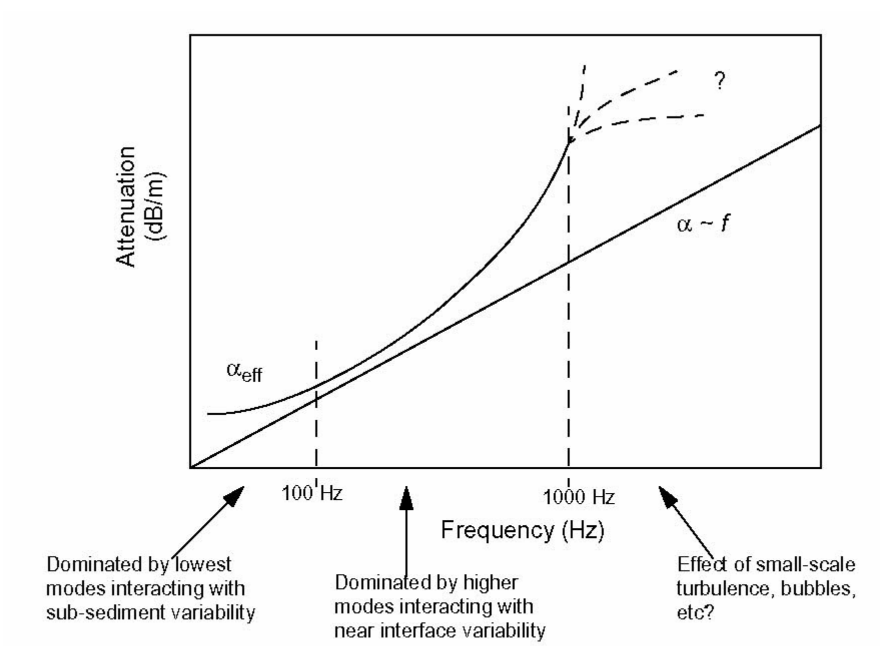

Figure 5: A proposed conjecture of effective attenuation results and their causes. Straight line shows standard linear frequency dependent model.

The analysis of the short-range water-bourne path is on-going. As of this date, an examination of the effects of turbulent strength and background sound speed on vertical coherence has been performed. Comparison with measured data is expected to occur within the near future.

Figure 6 displays the results of the peak vertical correlation on both the shallow and deep sub-arrays for the 50 m depth when the turbulent strength is varied to produce the indicated rms sound speed perturbations. Figure 7 displays similar results when the background sound speed profile is varied based on different averages on recorded CTD casts. As expected, the former case shows rapid decreases in signal coherence when the rms perturbations are increased. It is less clear, however, that background sound speed profile has a noticeable effect on the coherence structure.

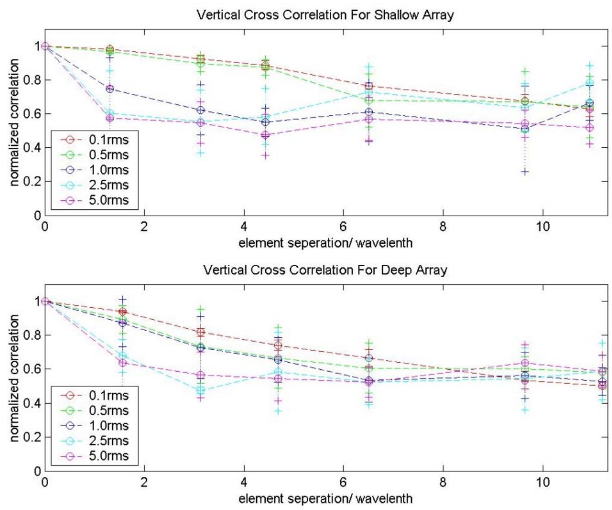

Figure 6: Peak vertical coherence curves of predicted propagation through variable turbulent strength fields for shallow (upper plot) and deep (lower plot) sub-arrays.

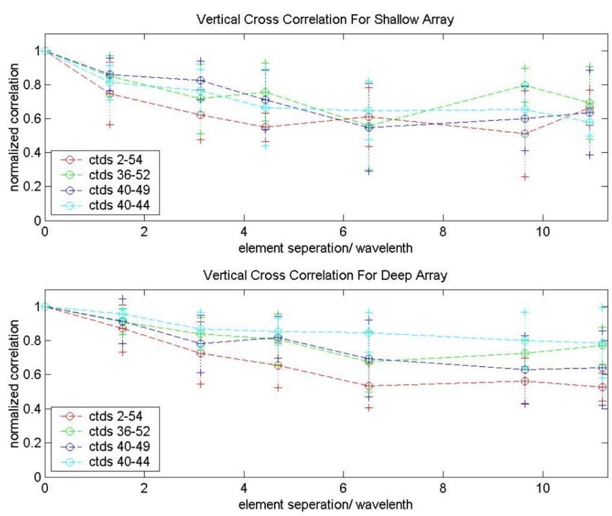

Figure 7: Peak vertical coherence curves of predicted propagation through turbulent perturbation with variable background SSPs for shallow (upper plot) and deep (lower plot) sub-arrays.

IMPACT/APPLICATIONS

The ability to distinguish reverberation signals from more general signal returns might lead to an improvement in the performance of active sonar systems. However, such distinction may require a more controlled broadband source with a flatter response. Understanding the influence of environmental variability on effective geoacoustic properties as well as short range propagation may lead to improved propagation prediction capabilities, thereby enhancing our ability to forecast system performance.

RELATED PROJECTS

Work on the reverberation analysis has included coordination with Ji-Xun Zhou of GA Tech and David Knobles or ARL-UT. Work on the effective attenuation of sediments has included collaborative discussions and plans for future joint analysis with Jim Miller and Gopu Potty of URI. Work on the direct path variability due to water volume turbulence has included collaborative analysis with Peter Dahl of APL-UW and Tim Duda of WHOI.

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